

LOWER EXTREMITY RESPONSE OF THE THOR-LX COMPARED TO THE HYBRID-III LOWER LEG IN FRONTAL BARRIER CRASH TESTS

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ABSTRACT

The Thor-Lx leg and foot complex is being developed by the National Highway Traffic Safety Administration (NHTSA), the Applied Safety Technologies Corporation, and GESAC, Inc. as a new research and development (R&D) tool which will be more biofidelic than the current Hybrid-III lower extremity. This paper reviews the results from a matrix of tests performed to evaluate the response of the Thor-Lx in comparison to the Hybrid-III lower extremity in high-speed frontal crashes. The testing included three 64 km/h frontal offset deformable barrier tests and two 56 km/h flat rigid barrier tests. Testing was done using the following Anthropomorphic Test Device (ATD) combinations: Hybrid-III with the Hybrid-III Enhanced Instrumented Tibia, Hybrid-III with the Thor-Lx, and Thor with the Thor-Lx.

The response of the lower extremity was found to vary with each leg and torso combination. Tibia bending moments were reduced and the lower tibia axial compressive force was increased in the Thor-Lx when compared to the Hybrid-III tibia. This phenomenon is attributed to the Achilles' tendon added to the Thor-Lx. When the Thor torso was used, loads measured in the lower extremity were lower than when the Hybrid-III torso was used. This lower level of loading is a result of changes in the torso kinematics that reduce the forward stroke of the pelvis.

INTRODUCTION

Advancements in automotive occupant restraint systems have been very successful in increasing occupant survivability in motor vehicle crashes. This has lead to a heightened awareness of the disabling lower extremity injuries often suffered by motor vehicle occupants during crashes. There has been a significant push in the automotive safety community to mitigate these injuries. To this

end, European Directive 96/79/EEC mandates lower extremity protection in offset frontal crash tests consistent with the EEVC WG11 protocol.

The EEVC protocol calls for measurement of the loads in the tibia of the Hybrid-III crash test dummy during a 56 km/h frontal crash into a 40% offset, deformable barrier. In this test, the loads measured by the Hybrid-III Enhanced leg are used to calculate a Tibia Index that is intended to predict the relative risk of fracturing the tibia bone.

This EEVC offset crash test is also conducted at 64 km/h for New Car Assessment Programs (NCAP) in Europe, Australia, and Japan. The Insurance Institute for Highway Safety (IIHS) is also conducting these tests at 64 km/h and publicizing the results through their publications and on North American television.

ATD Lower Extremities

Hybrid-III Enhanced Instrumented Tibia -

The ATD leg typically used by R&D and compliance laboratories to measure the lower leg loads in the Hybrid-III dummy is the Enhanced Instrumented Tibia. This device was developed from the Hybrid-III construction with enhancements to its data collection abilities. It is capable of collecting forces and bending moments at the proximal and distal ends of the tibia shaft (Figure 1).

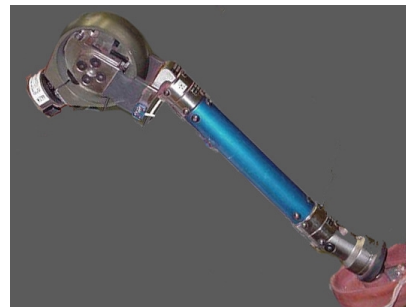


Figure 1. Hybrid-III Enhanced Instrumented Tibia.

The instrumented Hybrid-III tibia provides an objective measure of occupant protection and it gives insight into lower extremity loading which would otherwise be unavailable [Nyquist, 1978]. This has enabled automakers to develop vehicles with some level of leg protection incorporated into the design. Detailed studies such as the MIRA LLIMP Project [Payne, 1998] have used this instrumented leg to study the lower extremity kinematics during the crash event. This data is then used to help vehicle designers determine appropriate construction to minimize injury reference values measured by the ATD.

While the instrumented Hybrid-III leg may help to reduce injuries, concerns about its anatomical and response biofidelity have resulted in the need for an improved test device. NHTSA has taken on the challenge of developing a more biofidelic lower extremity as part of its Advanced Dummy Program [Ore, 1993].

Advanced Lower Extremity (ALEX) - The first device developed by NHTSA to improve upon the performance of the Hybrid-III tibia was the ALEX. This lower extremity was designed to be compatible with both the Hybrid-III and NHTSA's advanced frontal crash dummy, TAD. The design criteria for developing this leg were to improve the anthropometry, biofidelity, and measurement capabilities of the test device [Hagedorn, 1995].

The ALEX leg utilized a tibia construction similar to the Hybrid-III with improved measurement capabilities including anterior tibia load cells. The foot and ankle structure of ALEX was completely redesigned from the Hybrid III. The ankle was changed from a ball and socket joint to an orthogonal universal joint with rotary potentiometers applied to measure ankle rotation about the x-axis and y-axis. The foot was also redesigned to be a prosthetic type epoxy construction. This prosthetic type foot was intended to be more representative of the human foot because of its more flexible structure.

ALEX-II - Feedback received from testing done on the ALEX led to several significant design changes and the creation of ALEX-II [Hagedorn, 1998]. First, the tibia shaft was straightened because the offset orientation of the Hybrid-III tibia created an artifact in the measurement of tibia loads. In addition, an Achilles' tendon was added to represent the influence of the calf muscle's connection to the heel. The ankle joint and foot were redesigned to be more biofidelic in their anthropometry and response characteristics. Further, the anterior

tibia load cells were deleted because the data they provided was redundant.

Thor-Lx - In an effort to incorporate an advanced lower extremity into NHTSA's new advanced frontal crash test dummy, Thor, the ALEX-II design was merged with a competitive design being developed by GESAC, Inc. (Boonsboro, MD) [Shams, 1999]. The best aspects of each design were combined to create the Thor-Lx (Figure 2).

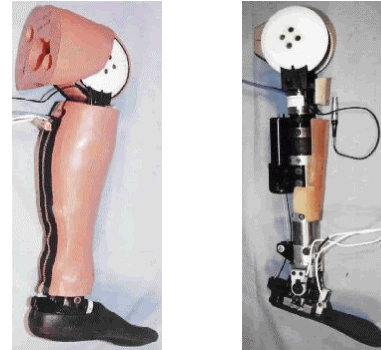


Figure 2. Thor-Lx [www.nhtsa.dot.gov].

The Thor-Lx was constructed with a straight tibia shaft and an Achilles' tendon. A compliant element was added in the tibia to allow for slight deformation in pure axial compression.

The ankle joint was derived from ALEX-II. It is designed to exhibit a continuously increasing torque angle response for both x-flexion and x-version by means of continuous joint stops. The resistance to dorsiflexion has three phases: minimal from -15° to 0° , moderate from 0° to 25° , and high from 25° to 45° . The response biofidelity was further improved through additional testing.

The foot consists of a carbon fiber sole plate and a Neoprene rubber heel pad. The version used for this testing incorporated two load cells on the plantar surface of the sole plate. These foot load cells were later removed from the design to help improve the impact response of the foot.

The instrumentation incorporated into the final Thor-Lx design includes two 4-axis tibia load cells, three rotary potentiometers at the ankle, one tri-axial accelerometer on the tibia shaft, one tri-axial accelerometer on the foot, and a uniaxial load cell on the Achilles' tendon.

Biofidelity of the Thor-Lx - The original biofidelity testing of the Thor-Lx was performed by the University of Virginia (UVA), the Transport Research Laboratory (TRL), and

Renault. Petit presented the results of Renault's testing at the 1999 Stapp Conference [Petit, 1999].

As a result of the first round of testing, a number of adjustments were made to the original Thor-Lx design. UVa assessed the second revision of the Thor-Lx and reported their results at the 1999 IRCOBI Conference [Rudd, 1999]. The leg, foot, and ankle assembly was found to produce a more biofidelic response for static tests including dorsiflexion, plantarflexion, inversion, and eversion than the Hybrid-III leg. The dynamic responses with respect to dorsiflexion and axial impacts were also improved. Finally, the tensile force measured in the Achilles' tendon is comparable to responses observed in cadaver testing [Shams, 1999].

Because of the differences in construction between the Enhanced Instrumented Tibia and the Thor-Lx, it is predicted that the two devices will exhibit different responses in frontal crash tests. It is important to understand how data collected from the Thor-Lx is different in order to develop vehicles in an efficient and effective manner.

TEST METHOD

Honda R&D conducted a series of five full vehicle impact tests using a 1999 model mid-size sedan as the program vehicle. Three 64 km/h Offset Deformable Barrier (ODB) tests and two 56 km/h Full-Lap Rigid Barrier (FRB) tests were conducted. The subject dummy was placed in the driver seat for each of the crash tests. The matrix of impacts modes and dummy configurations is shown in Table 1.

Table 1.
Vehicle Test Matrix

	Hybrid III + Inst. Tibia	Hybrid III + Thor Lx	Thor + Thor Lx
56 km/h FRB	○		○
64 km/h ODB	○	○	○

Anthropomorphic Test Devices (ATD)

The tests were conducted with three combinations of ATD components.

1. Hybrid III w/ Enhanced Tibia – For one test in each collision mode, the standard Hybrid-III crash test dummy with enhanced instrumentation was combined with the Enhanced Instrumented Tibia (R. A. Denton, Rochester Hills, MI). This configuration of ATD is commonly used in automotive crash testing.

2. Hybrid III w/ Thor-Lx – In one offset frontal crash test both legs on the Hybrid III ATD were replaced below the knee with the Thor-Lx device. This combination is considered to be a possible interim configuration for use to better assess lower extremity injury risk.

3. Thor w/ Thor-Lx – For one test in each collision mode, the upper body of the Thor advanced frontal crash test dummy was combined with Thor-Lx lower extremities. This full Thor ATD assembly is the foundation for future crash dummy developments.

Crash Test Setup

64 km/h Offset Deformable Barrier – The test vehicle was connected to a tow system and pulled to the point of impact at 64 km/h. The barrier was offset by forty percent of the width of the test vehicle and consisted of a rigid backing with a deformable face in accordance with the EEVC WG11 protocol for offset frontal crash testing (Figure 3).

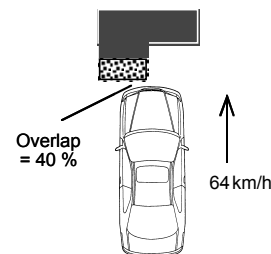


Figure 3. Offset Barrier Crash Test.

56 km/h Full Lap Rigid Barrier - The test vehicle was connected to a tow system and pulled to the impact point at 56 km/h. The vehicle impacted a rigid concrete barrier with the full aspect of the front of the vehicle. This test was performed according to the NHTSA test procedure for conducting frontal NCAP tests (Figure 4).

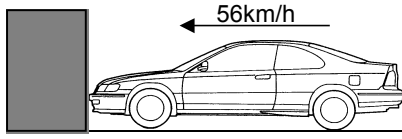


Figure 4. Full Lap Crash Test.

Data Acquisition

Instrumentation data from the vehicle and ATD was collected at a sampling rate of 10,000 Hz on a high G data acquisition system produced by Kayser-Threde (Munich, Germany).

TEST RESULTS

Vehicle Response

The deceleration responses of the program vehicle were reviewed for each test mode to ensure that the different ATD configurations were exposed to similar crash dynamics. The accelerations recorded at the center of gravity of each vehicle show consistent performance in each of the two crash modes (Figures 5, 6).

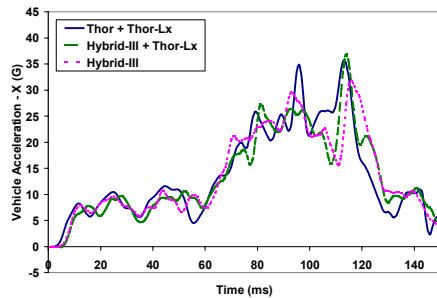


Figure 5. 64 km/h ODB Crash Pulse.

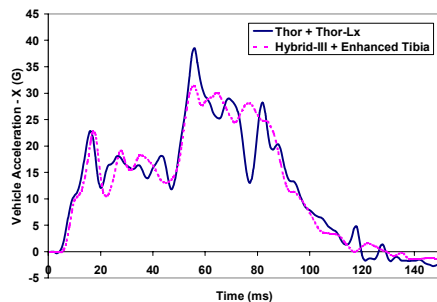


Figure 6. 56 km/h FRB Crash Pulse.

ATD Response

The main data channels reviewed in this paper are those of the tibia load cells because these channels are consistent between the two test devices. Additional channels have been included to help analyze the responses that were observed. These additional channels include pelvis acceleration, ankle rotation, and Achilles' tendon load.

In order to maintain clarity, we will review the left tibia in the ODB crash mode. The left leg was chosen because of its more stable response due to its placement on the footrest. Analysis of the right leg is complicated because of the interaction with the accelerator pedal. Additional data traces for the right leg and FRB crash mode can be found in the appendix.

Upper Tibia Load Cell – For both the ODB and FRB crash modes, the upper tibia load cell shows lower axial loads (Fz) in the cases where the entire Thor dummy was used. Axial loads were very similar between the Hybrid-III tibia and Thor-Lx when the Hybrid-III torso assembly was used in the ODB test mode. Figure 7 illustrates this phenomenon.

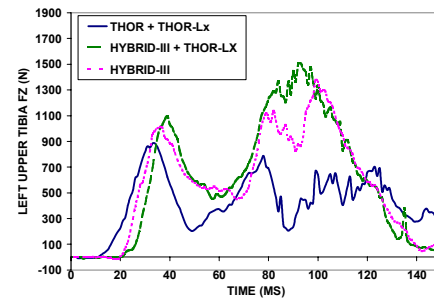


Figure 7. Left Upper Tibia Fz in the ODB.

Lower Tibia Load Cell – Instrumentation data recorded from the lower tibia load cell includes axial force, A/P shear force, and non-torsion bending moments. The most interesting of these data channels are the bending moments and axial compression because of the role that they play in determining the Tibia Index.

In all tests, the axial compressive forces (Fz) on the lower tibia load cell were higher in the Thor-Lx than they were in the comparable Hybrid-III tibia. Figure 8 illustrates the higher loads measured in the lower tibia. It is also observed that the Thor + Thor-Lx combination has a lower compressive load than the Hybrid-III + Thor-Lx in the ODB test mode.

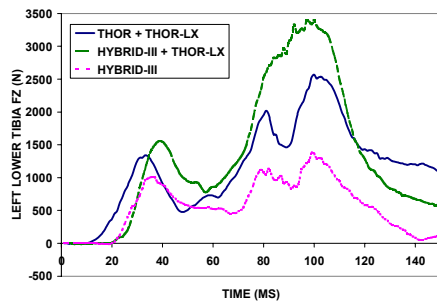


Figure 8. Left Lower Tibia Fz in the ODB.

The dorsiflexion/plantarflexion moment (My) also exhibits a different response in the Thor-Lx than in the Hybrid-III tibia. Data from the left lower tibia load cell in the ODB crash, Figure 9, shows a negative moment in dorsiflexion, while the Hybrid-III exhibits a negative moment initially, but then becomes positive later in the event. The left tibia in the FRB crash modes has the same response trend.

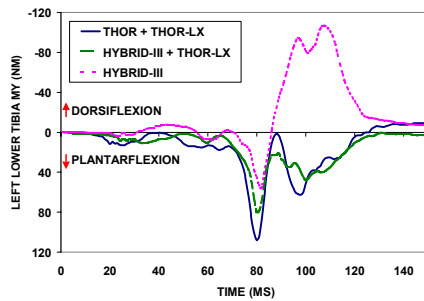


Figure 9. Left Lower Tibia My in the ODB.

Figure 10 shows the lower tibia load cell data from the right leg in the ODB. Because of the higher dorsiflexion forces, this graph helps to more clearly illustrate the effect of the Achilles' tendon on the distal tibia bending moments. The My data from the Hybrid-III tibia is greater than in either test using the Thor-Lx. The bending moment is lowest when the complete Thor assembly is used.

Data collected for the inversion/eversion, Mx, bending moments exhibited a less clear response differentiation between the test devices. Clearly shown in the Mx data was the effect of the continuous joint stops. The Mx response of the Hybrid-III is not evident until the joint 'bottoms out' then the Mx starts to rise significantly. With the Thor-Lx assembly, the Mx moments rise continuously with rotation (Figure 11).

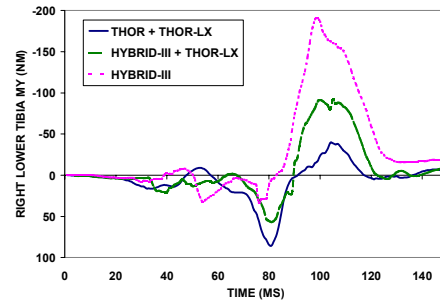


Figure 10. Right Lower Tibia My in the ODB.

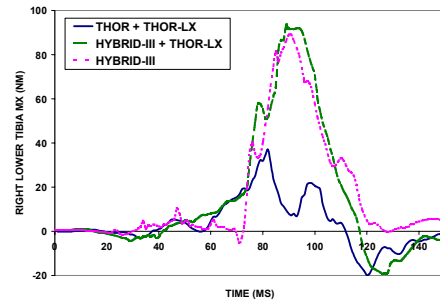


Figure 11. Right Lower Tibia Mx in the ODB.

Pelvis Movement – The lower extremity loads measured in the test where the Hybrid-III torso was used were generally higher than those from comparable tests using the Thor dummy. By looking at the acceleration of the pelvis as a function of movement relative to the vehicle (G-S), it was possible to understand the differences in dummy kinematic responses (Figure 12). This data suggests there was substantially less forward pelvis movement in the tests where the Thor assembly was used.

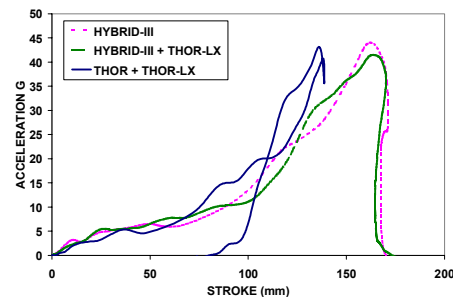


Figure 12. Pelvis Movement in the ODB.

Ankle Rotation – Ankle rotation data was only collected from the Thor-Lx because the Hybrid-III device was not outfitted with instrumentation to collect this data. Figure 13 shows traces of the ankle rotation as a function of time.

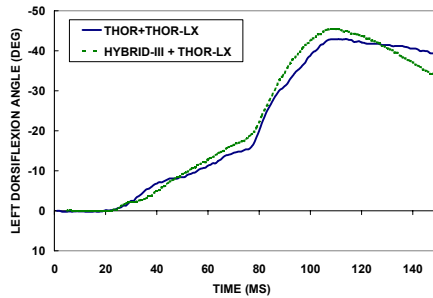


Figure 13. Thor-Lx Left Ankle Dorsiflexion Angle in the ODB.

Achilles' Tendon Loads – Figure 14 shows the data recorded from the Achilles' load cell. The load data has a two-phase response. The first phase has a very low level of resistance followed by a second phase that has a high level of resistance and a rapid rise up. The timing of these two phases is coincident with data collected from the y-axis rotary potentiometer. A graph of the Achilles' force as a function of dorsiflexion angle is shown in Figure 15.

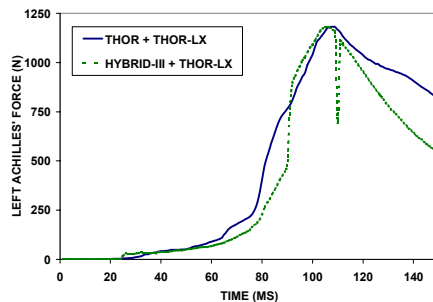


Figure 14. Left Achilles' Tendon Tension in the ODB Mode.

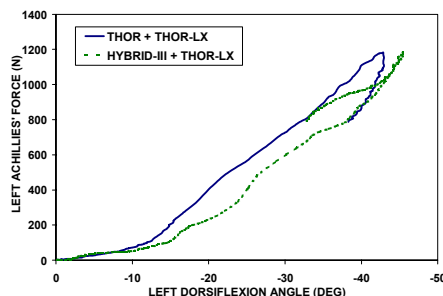


Figure 15. Left Achilles' Force vs. Dorsiflexion Angle in the ODB Mode.

Acceleration Data – Data was collected from uniaxial accelerometers on the knees of each dummy and from triaxial accelerometers on the tibia and foot of the Thor-Lx. The foot of the Hybrid-III leg was also instrumented with foot x- and z-axis accelerometers. This data was not closely reviewed for these proceedings.

DISCUSSION

Lower extremity injury data varied greatly depending on the combination of dummy and lower extremity chosen. The differences observed in the data can be classified into two phenomena. One is related to the differences in the kinematic response of the dummies and the other rises from the effect of the Achilles' tendon.

Dummy Kinematics

The upper body responses of the two ATD's are significantly different. This is evident in the longitudinal pelvis acceleration measured in each of the tests. In the pelvis stroke data, it is clear the Thor ATD has much less forward pelvis movement than the Hybrid III (Figure 12). This is likely due to differences in the restraint system interactions of the two dummies.

The shorter stroke of the Thor pelvis results in less loading through the lower extremity. This is demonstrated in the loading trends observed in the different tests. The upper tibia load cell data shows consistently higher axial loads when the Hybrid III torso is used than when the Thor is used (Figure 7). This same trend is also present in the axial load data collected from the lower tibia load cell (Figure 8), however the distinction becomes less clear because of the presence of the Achilles' tendon.

Achilles' Tendon Phenomenon

Axial Load, Fz - The construction of the Thor-Lx places the lower tibia load cell between the origin and insertion of the Achilles' tendon. This results in the tensile force of the tendon being reacted through the load cell as illustrated in Figure 16. As the foot is moved in dorsiflexion, the tendon is loaded and generates an axial force through the tibia shaft. This reactive force increases the loads already being measured by the lower tibia load cell.

This phenomenon of increasing the lower tibia axial force measurement was predicted during the development on Thor-Lx [Shams,

1999]. This is because the lower tibia load cell is designed to be in the load path of the Achilles' tendon. This effect was also observed in testing done by the OSRP in which they compared the Hybrid-III with Thor in full vehicle crash tests [Xu, 2000].

Examination of a force-moment diagram (Figure 16) illustrates how the axial force measurements in the Thor-Lx are different from those measured in the Hybrid-III. The axial tibia loads in the Hybrid-III are typically a function of the vertical loads experienced by the foot. In the Thor-Lx, the Achilles' tendon affects the axial load measured by the distal tibia load cell. The effect of the tendon is to react the dorsiflexion moment about the ankle resulting from loading of the forefoot. The force of the Achilles' tendon is reacted along the axis of the tibia between its origin and insertion on the leg. The reacting force of the tendon causes an increase in the compressive load at the distal tibia load cell.

Bending Moment, M_y – Placement of the lower tibia load cell in the Achilles' load path means that bending moments recorded by the load cell will also be effected. The tendon applies a counter-moment to the bending moment induced by dorsiflexion of the foot. This results in a reduction in the measured lower tibia bending moment as can be seen when comparing the response of the Hybrid-III to the response of Thor (Figures 9, 10).

CONCLUSIONS

The data presented in this paper finds that the lower extremity response of the Thor ATD is different from the response of the Hybrid-III.

Loading of the lower extremity by the upper body mass differs between the two ATDs. This is a result of the different torso kinematics that is illustrated by the pelvis stroke response. The Hybrid-III experiences more forward pelvis movement than the Thor. Consequently the loads measured in the lower extremity are higher for the Hybrid-III assembly than for the Thor assembly.

The measurements obtained from the instrumentation of the lower extremity are also effected by the construction of the leg. Application of an Achilles' tendon to Thor-Lx increases the axial compressive force in the distal tibia. At that same location, the bending moment (M_y) is decreased. These changes in the measured loads result from the distal tibia load cell being located within the load path of the Achilles' tendon.

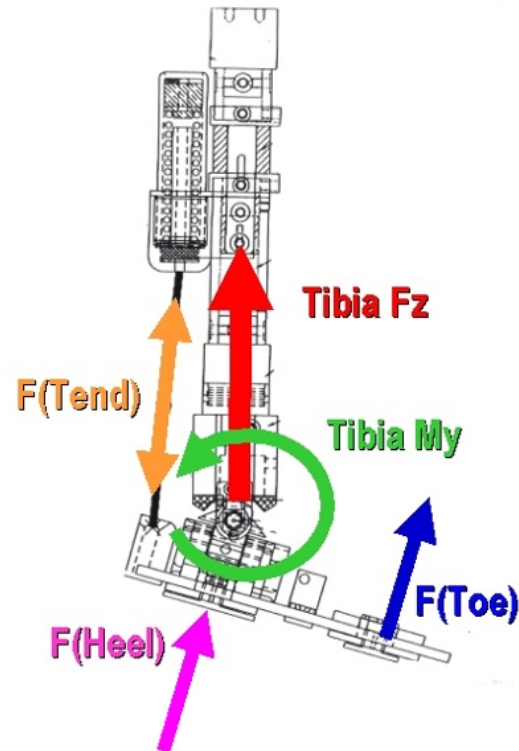


Figure 16. Tibia Force-Moment Diagram.

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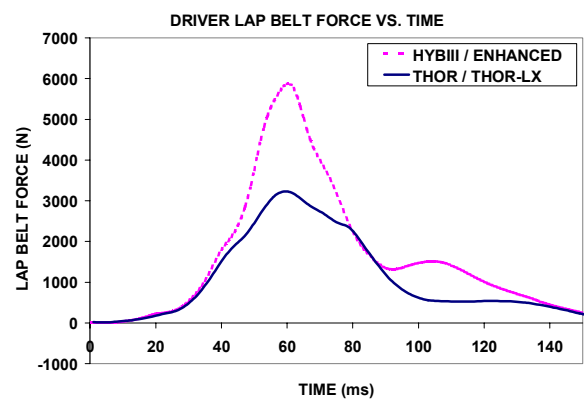
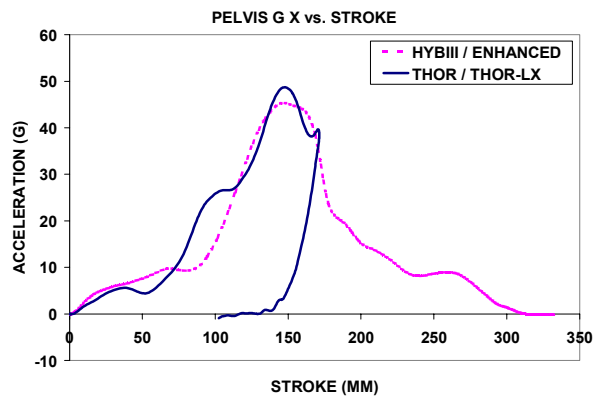
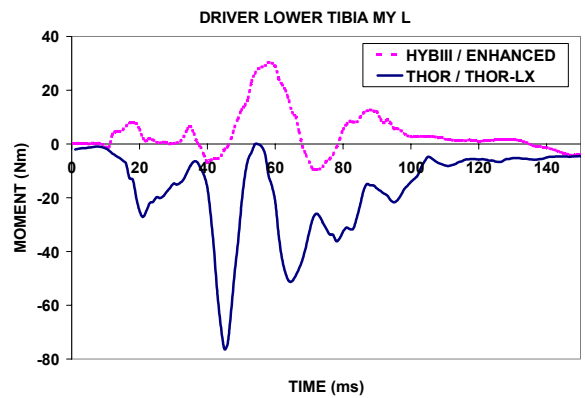
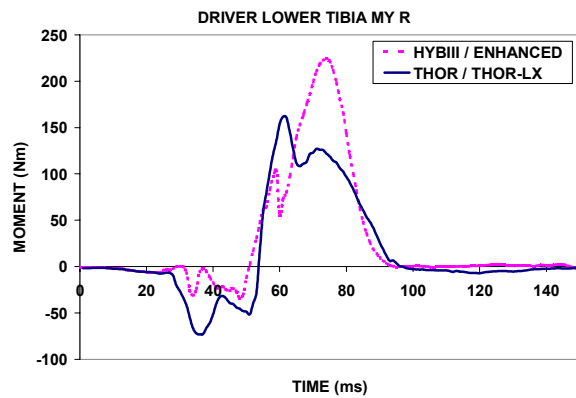
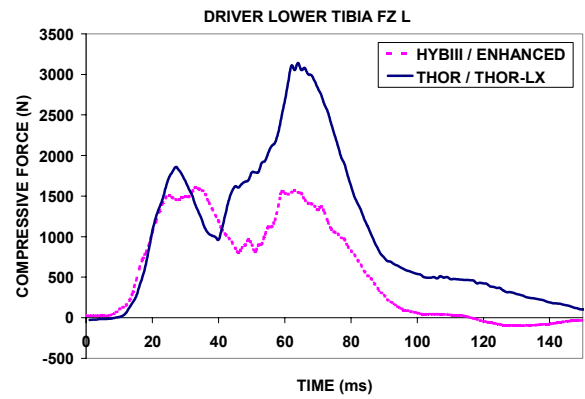
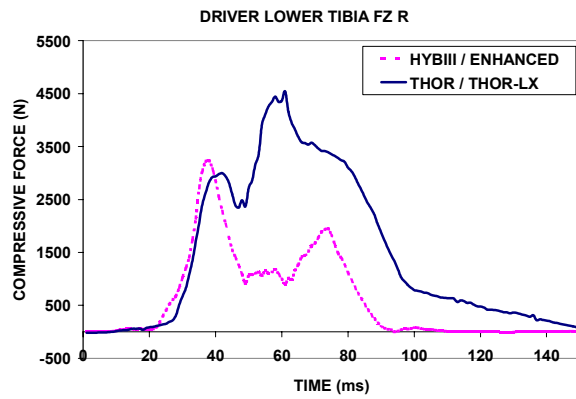
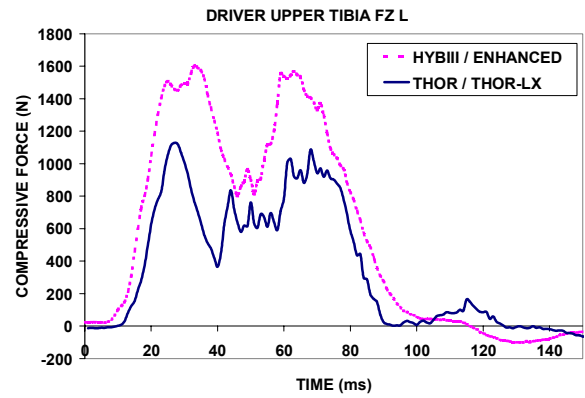
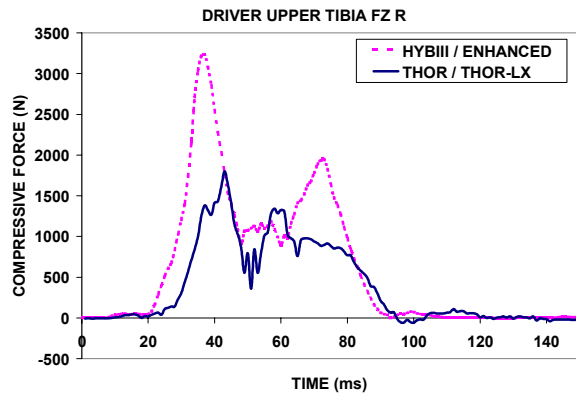
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APPENDIX – 56 km/h FRB



APPENDIX – 64 km/h ODB

